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Abstract

This paper compares of snowpack accumulation and ablation, evapotranspiration, and water outflow from clearcut and forested plots within a high elevation (2900 m) mixed conifer forest at the Fraser Experimental Forest near Fraser, Colorado, USA. Also presented is a method for defining contributing area where outflow is measured from unbounded plots. Plots were monitored from 1980 to 1990 and again in 1993. The clearcut plot was harvested in late 1984. Evapotranspiration (E_T) of the forested plot at zero discharge (E_{To}) was estimated at 426 mm while the E_T was 500 mm at the mean precipitation of 596 mm. E_T was dependent on precipitation with about 28% of precipitation input in excess of 426 mm contributing to increased E_T, while the remainder contributed to increased outflow. During the six monitored post-harvest years, Peak Water Equivalent of the snowpack averaged 36% higher on the cut plot than on the control, and the mean discharge increased from 85 mm to 356 mm.

Area estimates were obtained from the slopes of the regression of outflow on precipitation inputs. Hydrologic parameters corresponded closely to those previously determined at Fraser Experimental Forest using other methods, lending credence to the validity of the area estimates.

Introduction

The influence of harvest practices on snow accumulation and stream flow has been studied at the Fraser Experimental Forest (FEF) for more than half a century. These studies, reviewed in depth by Meiman (1987) and Troendle and Kaufmann (1987), have demonstrated consistent increase in both snowpack accumulation and stream flow as forest density is decreased by tree removal. However, most of the snowpack deposition studies were either plot studies not tied directly to water outflow or, if at the catchment level, were related only to water outflow on a whole catchment basis where tree removal was less than complete. This report compares snowpack accumulation and ablation, evapotranspiration, and water outflow on clearcut and forested plots within a mixed conifer forest, and presents a method for estimating contributing area where outflow is measured from unbounded plots. Preliminary data were reported by Troendle (1985, 1987) and Troendle and Nilles (1987). Chemical inputs and outputs were also monitored and are available in Reuss *et al.*, (1997).

Site Description

The FEF is located 137 km west of Denver, Colorado. The study area is located at FEF on a 10 ha segment of a lateral moraine at 2900 m elevation. The hillslope is west facing, has a uniform 30% slope, and is fully forested with 210 m^3 ha^{-1} Engelmann spruce (*Picea engelmannii*), subalpine fir (*Abies lasiocarpa*), lodgepole pine (*Pinus contorta*), and an occasional aspen (*Populus tremuloides*). The soil, a coarse-loamy mixed Dystric Cryochrept (formerly Leal sandy loam), is distributed uniformly on the slope and is underlain with a relatively impermeable clay subsoil. The bedrock is dominated by gneiss and schist. The long-term mean annual precipitation at the forest headquarters (2725 m) is 580 mm, most of which falls as snow. Long-term catchment studies indicate annual E_T, estimated as precipitation minus measured stream flow, ranges from 450 to over 570 mm per year depending on precipitation amount (Troendle, 1987b, Troendle and Kaufmann, 1987), and annual E_T can be reduced by as much as 400 mm, in a very wet year, following timber harvest (Troendle and King, 1985).

Methods

In 1978 and 1979, two surface/subsurface flow collection systems were installed in trenches excavated at the base of, and perpendicular to, the hillslope, on separate portions of the study site. They were designed to intercept and monitor the surface and subsurface migration of water downslope and follow the techniques of Whipkey (1967).

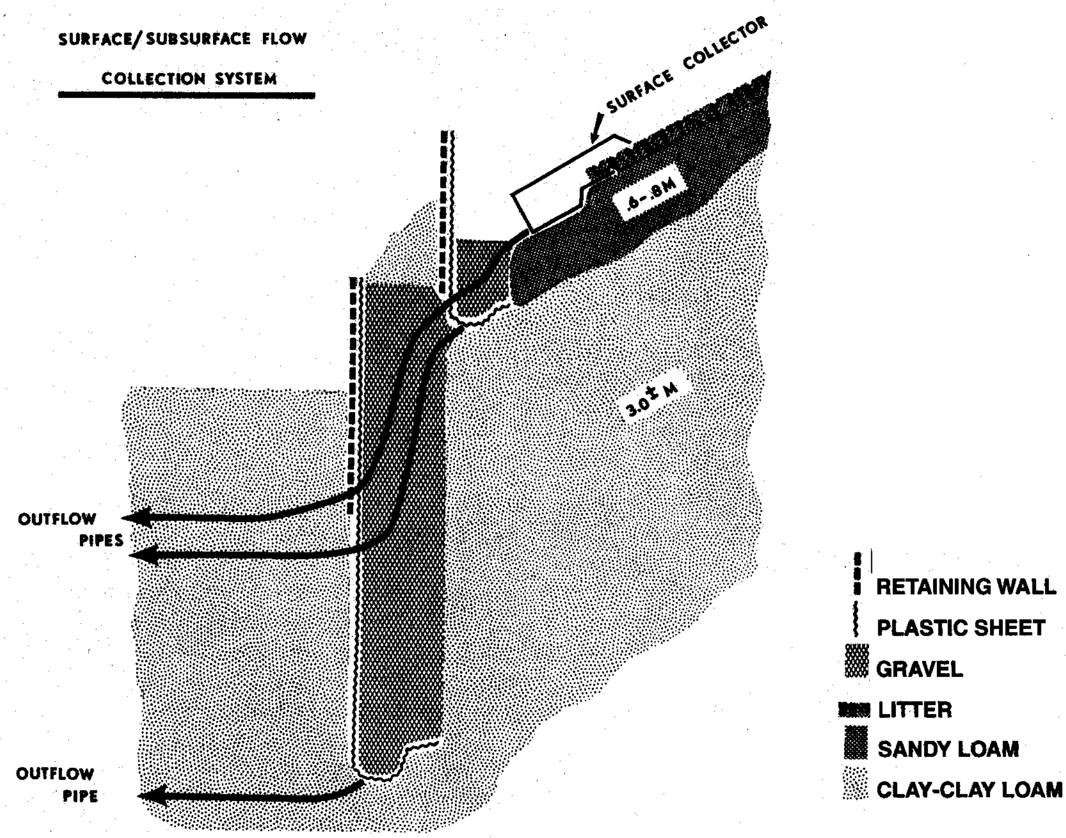

Fig. 1. *Vertical schematic of a surface/subsurface flow collection system (from Troendle, 1985).*

Figure 1 represents a vertical schematic of the collection systems used on both plots. Flow, moving more or less horizontally in a downslope direction, was collected from the surface (on or above the mineral soil); from the shallow subsurface which included the developed horizons, i.e., from the mineral soil surface to the interface of the sandy clay loam/clay loam at about 1 m deep; and from the deeper subsurface, i.e., below the shallow subsurface to a depth of about 4 m. The method of installation has been described by Troendle (1985). Flow intercepted from each layer (surface, shallow subsurface, and deep subsurface) is routed downhill, via a piping system, to individual H or HS flumes, each fitted with a water level recorder. Flow was monitored from 1980 through 1990 and again in 1993. The collection system on plot 1, about 12 m long, was installed perpendicular to the fall line at the toe of the 210 m slope at the southwest end of the 10 ha study area. The hillslope contributing to the collection system on plot 1 is somewhat divergent. The collection system on plot 2 was longer, about 36 m, and was installed across a small swale at the center of the 10 ha study area. The hillslope contributing to the second system is converging in nature.

In addition to the flow collection systems, piezometric wells fitted with gas bubbling recorders (Helmers, 1968) were installed to monitor the dynamics of perched water tables on the hillslope. Twenty-seven neutron probe access tubes were installed to monitor soil moisture contents to a depth of 3 m. Neither the piezometric data nor the neutron probe data are reported here. However, the piezometric wells were used to estimate the hydraulic conductivities reported, and the access tube locations served as permanent markers for sampling the snow water equivalents reported. The study area layout is presented in Fig. 2.

A seismic survey indicated that soil layering was relatively uniform over the entire study area. The average depth of the interface between the more porous, developed surface horizons and the finer textured material is 1.2 m. Seismic velocities indicated a second major textural break at 3–6 m below the surface, and this break was shallowest on the mid to lower slope, about 50–100 m above the collection systems (Troendle, 1985). Estimated saturated conductivity in the soil about the piezometric wells varied markedly with depth (Troendle, 1985). Conductivity is as great as 120 cm hr^{-1} at the surface, 12–15 cm hr^{-1} in the upper metre of soil, 1 cm hr^{-1} at 2 m depth and too slow to measure at 3 m, using the shallow-well pump-out method of Boersma (1965).

The contributing area for the two flow collection systems, or actual plot sizes, could not be defined at the time

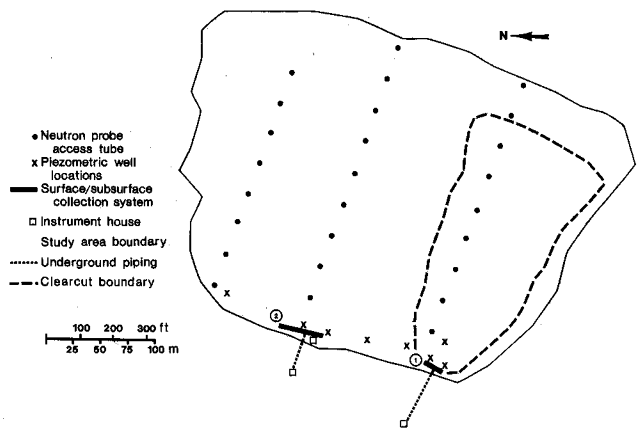

Fig. 2. *Schematic diagram of the surface/subsurface flow study area (from Troendle, 1987).*

of installation but the surface area of the rectangle (length × trench length or width) represented by plot 1 is 0.3 ha and for plot 2 is 0.8 ha. Based on the seismic measures of surface/subsurface topography, the hillslope on plot 1 is divergent, implying the actual contributing area may be less than the rectangular estimate of 0.3 ha, while the slope on plot 2 is convergent, implying the contributing area may be greater than the rectangle (length × width) area of 0.8 ha (Troendle, 1985).

Initially, summer precipitation was monitored on-site, using a weighing-bucket recorder located in a natural opening in the forest, but the estimate proved to be the same as that recorded at the nearby FEF headquarters gauge; so the recorder on-site was removed, and on-site estimates of summer precipitation (rainfall) were made from the headquarters site. Winter precipitation was estimated as the Peak Water Equivalent (PWE) in the snowpack on or about 1 April. Snow water equivalents were measured each year at the 27 locations of the neutron probe access tubes using a Federal snow tube ànd scale. Seven of the 27 sites were specific to plot 1 and nine were specific to plot 2 (Fig. 2). In some years, measurements were taken bi-weekly throughout the melt period. At the time of installation, a 1 m area around each access tube was cleared of woody debris (slash) to facilitate snowpack sampling and the sampling sites were maintained free of debris following timber harvest. This ensured a consistent index to winter snowpack accumulation.

In December 1984, the entire area including and around plot 1 was clearcut (about 3 ha), with only the boles removed from the site. The harvesting operation was conducted in the winter to minimize impact to the soil surface. No access roads were constructed on the study area and tree boles were winched or dragged off-site. All merchantable material (sawlogs, poles, posts, and fuelwood) was removed and the tree branches scattered uniformly over the plot. In the spring of 1985, all remaining vegetation was cut down. At the completion of harvesting, none of the pre-harvest living vegetation remained. Regeneration was allowed to occur naturally. By 1993, approximately 2,500 tree stems per ha. had regenerated and were 0.1-0.2 m tall. Based on earlier catchment experiments at Fool Creek and Deadhorse Creek, also on the Experimental Forest, it would be concluded that regeneration, following harvest, would have had little or no measurable effect on snowpack accumulation or the water balance of the clearcut plot during the period reported. (Troendle and King, 1985, 1987).

Results

PRECIPITATION

Annual precipitations for water years (Oct/Sep) 1977 to 1993 are summarized in Table 1. Mean annual precipitation for this period was approximately 596 mm, ranging from 467 mm in 1981 to 837 mm in 1984. Seasonal precipitation patterns are somewhat irregular with no well-defined wet or dry seasons, but the differences in monthly precipitation are significant statistically, ($P < 0.001$), ranging from a low of 37 mm in October to a high of 67 mm in May. The distribution appears to be trimodal with highs in November, May, and July and lows in October, February, and June.

Table 1. *Total precipitation by water year (Oct/Sep).*

Year	Oct/Sep
	mm
1977	505
1978	524
1979	554
1980	578
1981	467
1982	653
1983	737
1984	837
1985	619
1986	649
1987	506
1988	610
1989	554
1990	569
1991	591
1992	52.
1993	648
Mean	596
Std dev	92
Std err	23

Table 2. *Mean snow water content on or about 1 April.*

Years		Plot 1 Clear cut	Plot 2 Control
		mm	mm
1980		290	290
1981		136	140
1982		206	181
1983		284	270
1984		345	345
1985		217	188
1986		251	210
1987		214	143
1988		346	240
1989		308	234
1990		301	209
1993		377	284
1980–84	mean	252	245
	s.d	82	83
1986-93	mean	300	220
	s.d	60	47
all	mean	273	228
	s.d	70	62

Note: Only average of plots 1 and 2 available for 1980 and 1984. Used for both plots.

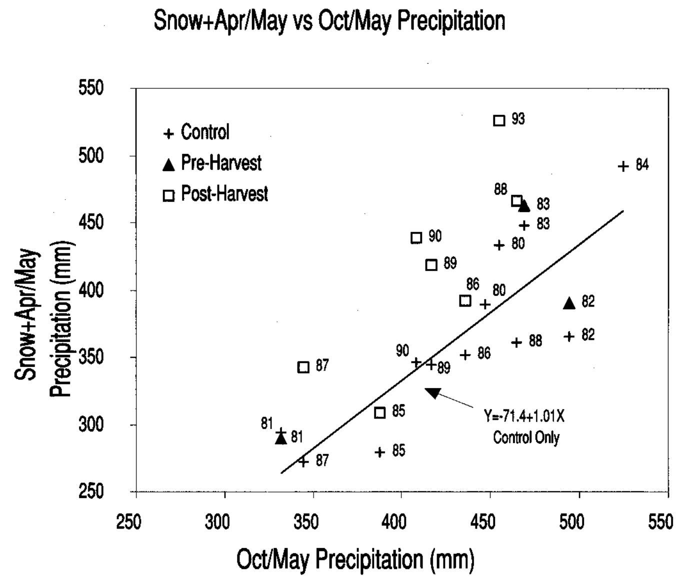

Fig. 3. *Snow accumulation (mm H_2O) plus Apr/May precipitation on site versus Oct/May precipitation, at the headquarters raingage, for control, pre-harvest and post-harvest clearcut plots. Regression line represents the relationship for the control plot data.*

Snowpack accumulation measurements (Table 2) started in 1980. During the 1980-84 period, snowpack PWE on or about 1 April averaged approximately 250 mm on both plots. After harvest, PWE in the clearcut encompassing plot 1 averaged 36% higher than in the forest associated with plot 2. This increase is very similar to the 34% increase predicted by Troendle for the removal of 100% of the basal area on neutral, i.e., east- or west-facing slopes (Troendle, 1987). Figure 3 shows an winter season precipitation (total snowpack accumulation plus Apr/May precipitation) plotted as a function of the total Oct/May precipitation measured at FEF headquarters gauge for the years prior to and after the harvest of the area representing plot 1. The regression line, on Fig. 3, represents the best fit relationship between snowpack accumulation plus Apr/May precipitation on plot 2 (control) versus Oct/May precipitation measured at headquarters. The slope of 1.01 indicates the strong similarity. Pre-harvest estimates for plot 1 are also presented and are compared with the fitted values. The estimates for plot 1, after harvest, are quite elevated. The slope of the line fitted to the post-harvest data for plot 1 (not shown) is 1.4 and is consistent with the increased throughfall associated with vegetation removal (Troendle, 1987).

AREA ESTIMATION

The initial estimate of plot size, based on collector length, or plot width, and slope length, was 0.3 and 0.8 ha for plots 1 (clearcut) and 2 (control) respectively. Total discharge (combination of surface and subsurface flow) from plot 1 over the 1980 to 1984 period, i.e., prior to clear cutting, was 788 m^3 while discharge from plot 2 (control) was 12,464 m^3. The ratio of the total pre-harvest discharge from the two plots is about 15.8 to 1, much larger than the ratio of 2.67 to 1 that would be expected if the rectangular plot sizes were appropriate measures of the contributing areas. A similar ratio (16.7 to 1) is reflected in the slope of 0.060 for a regression of annual pre-harvest plot 1 discharge on plot 2 discharge. Assuming minimal errors in measuring discharge, these rectangular areas (0.3 and 0.8 ha) cannot reflect the actual contributing areas accurately. To express outflow on a volume per unit area basis, i.e., depth, estimates of the true drainage areas must first be developed.

Firstly, consider a very simplistic model, i.e.,

$$Q = (P - E_T)A \tag{1}$$

where Q is discharge, P is precipitation, E_T is evapotranspiration, and A is area. Assumptions inherent in the use of Eqn. (1): E_T includes all forms of return of water to the atmosphere, i.e., evaporation, transpiration, and sublimation; annual change in soil water storage is negligible; and all deep percolation is captured in the measured outflow.

Table 3. *Estimation of plot area by regression of volume discharge on precipitation input. See text for model description.*

Precip cycle	Model	Plot	df	Area	S.E. Area	Intercept	S.E. Intercept	R^2
				ha	ha	mm	mm	
Oct/Sep	full	Cont	19	1.173	0.091	462	14	0.95
	partial	CC	9	0.078	0.016	119	107	0.74
Snow+	full	Cont	19	1.639	0.170	253	14	0.90
Apr/May	partial	CC	9	0.109	0.022	85	76	0.74

Equation 1 represents a straight line where Q is expressed as function of P, and E_T is the intercept with the P axis. If Eqn. (1) is valid for this situation, then a plot of discharge as a function of precipitation will give a straight line with slope A, and the P axis intercept will be an estimate of E_T. While Eqn. (1) may not be completely valid for any particular year due to variation of water storage in the soil mantle, the average slope generated by plotting data for a number of years will approximate a true estimate of area if E_T is independent of precipitation. The latter is a significant constraint that will be discussed further below. The soil moisture variable was not included in the model; extensive experience monitoring soil moisture depletion on similar plots nearby indicates consistent differences, from 50–70 mm, in seasonal soil water depletion between forested and clearcut plots, (Troendle, 1987, Troendle and Meiman, 1986, Wilm and Dunford, 1948). It was considered that including a component for soil moisture storage differences could introduce more error than it has the potential to explain.

Equation 2 is an expansion of the model in Eqn. (1) that would apply to two plots of different areas.

$$Q = A_1(x_1 - c)d_1 + A_2(x_2 - c)d_2 \qquad (2)$$

Here, Q is the volume discharge; x_1 and x_2 are the precipitation values that apply to plots 1 and 2 respectively; c is the overall evapotranspiration which is assumed constant for both plots in this model; A_1 and A_2 are the slopes, i.e., the areas for the respective plots; while d_1 and d_2 are dummy variables. For a Q value from plot 1, d_1 is assigned a value of 1, and d_2 is assigned a value of 0. Conversely, if the Q value is from plot 2, d_1 is assigned a value of 0 and d_2 a value of 1.

The model becomes slightly more complex when a module for the post-harvest years from plot 1 is incorporated. Post-harvest discharge from plot 1 is much higher relative to the control than is pre-harvest discharge. Apparently, this increased discharge arises from two sources, increased snow accumulation and decreased E_T, (i.e., c in Eqn. (2)), resulting from the removal of canopy. Because the area remains the same, the slope of a plot of volume discharge vs. precipitation should be the same for both the pre-harvest and post-harvest condition. However, because post-harvest E_T is lower than pre-harvest E_T, discharge increases, and the intercept on the precipitation axis will be below that from the pre-harvest situation. Based on the above assumptions the complete model would be

$$y = A_1(x_1 - c_1)d_1 + A_2(x_2 - c_1)d_2 + A_2(x_3 - c_2)d_3 \qquad (3)$$

In this case x_1, x_2, and x_3, are the precipitation values that apply to the control, clearcut pre-harvest, and clearcut post-harvest respectively; A_1 and A_2 are again the areas of the control and clearcut plots, respectively; c_1 is the E_T for the control and the clearcut pre-harvest case, and c_2 is the E_T for the clearcut post-harvest case. The dummy variable d_1 takes the value of 1 if the y value is from the control, otherwise it is zero,. Similarly d_2 takes the value of 1 only if the y value is from clearcut pre-harvest, while d_3 assumes a value of 1 only if the y value is from post-harvest clearcut. This model is constrained to a common slope (area) for the pre-harvest and post-harvest cases on plot 1, and a common intercept (E_T) for plot 2 and pre-harvest plot 1.

The model shown as Eqn. (3) was applied using two estimates of precipitation input, the first being the estimate for the entire water year (Oct/Sep), and the second being the measured snowpack (ca 1 April) plus Apr/May precipitation. While reasonable values are generally obtained from this model, the standard errors for the area (A) of plot 2 and the post-harvest intercepts are unrealistically high, the high discharge values from the larger control plot are associated with a much higher error term than would be appropriate for the smaller clearcut plot. This large error dominates the pooled error term in the complete model, resulting in unrealistically high standard errors for those parameters associated only with plot 1. However, after running the complete model to estimate plot 2 area and the E_T for plot 2 and pre-harvest plot 1, one can use a partial model for plot 2 only. This consists of only the second and third terms in Eqn. (3) and is constrained by entering the value of c_1, i.e., the intercept from the control and the pre-harvest clearcut, as determined from the full model. Estimates of the post-harvest intercept and the plot 1 area obtained with this model are nearly identical to those from the full model but, as only the smaller plot 1 discharge values are used, the error terms are no longer dominated by the higher plot 2 values. Therefore, the associated standard errors for plot 1 area and post-harvest E_T are much more appropriate, and standard errors reported in Table 3 for plot 1 area and the post-harvest intercept are derived from the partial model.

The plot area and control E_T estimates from the Oct/Sep full year cycle, are 1.17 ha for plot 2 and 0.078 ha for plot 1, with a control and pre-harvest E_T of 462 mm (Table 3). The full year regressions have the advantage that, while yearly variations in actual E_T may contribute to scatter, the 460 mm value should be a reasonable estimate of E_T at zero discharge, i.e., E_{To}.

The snowpack water equivalent plus Apr/May precipitation (Table 3) was included because summer E_T exceeds precipitation so that only winter and spring moisture contribute directly to discharge. Also, any dependence of E_T on precipitation should be of much less importance during the winter. Intercepts derived from this part-year cycle cannot be regarded as an estimate of E_{To}, but reflect recharge of soil moisture depletion plus some winter and spring E_T. The area estimates derived using snow plus Apr/May precipitation are 1.639 ha for plot 2 and 0.109 ha for plot 1. The estimated ratio of plot 2 to plot 1 area is 15.0 to 1 for both precipitation cycles, which agrees quite well with the 15.8 to 1 value suggested by the ratios of the pre-harvest discharge volumes. Plots of volume discharge as a function of snow plus Apr/May precipitation are shown in Fig. 4. A reasonably linear relationship between discharge and precipitation is apparent, with the post-harvest line for plot 1 lying above the pre-harvest line as expected.

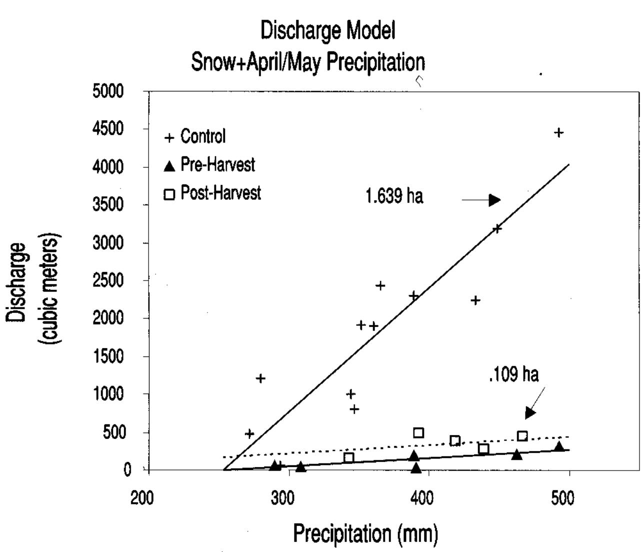

Fig. 4. *Yearly volume discharge (m^3) as related to snow plus Apr/May precipitation. The areas are estimated by the slopes as shown in Table 3.*

The area estimates based on winter precipitation (snowpack PWE on April 1 plus April/May precipitation) are preferred over those based on the full year cycle since they contribute most directly to the measured discharge. Since slope has the dimensions of area, it is unlikely the area calculated from this would exceed the true area significantly. If it did, an increment of precipitation would result in a greater increase in discharge than the volume of water contained in that increment. Furthermore, direct measurements of the snowpack are not subject to the vagaries of interpreting snow inputs based on precipitation gage values. The April/May precipitation usually occurs as heavy snow or rainfall at this elevation and is not as subject to measurement (gauge) error as are the cold snowfall events.

The most likely explanation for the low estimates of area derived from the full year cycle is that over the full year, E_T tends to increase with precipitation. This is particularly true for summer precipitation because summer precipitation is lost on-site regardless of vegetation density (Troendle and King, 1985, 1987, and Troendle, 1987b). The effect would be to decrease Q to a value less than that which would be predicted by Eqn. (3) if a constant E_T were assumed, thus decreasing the slope of the plot of Q against P. While this would affect the slope of the plot, it probably would not have much effect on the intercept, which would have to be considered as the E_T value at the precipitation at which minimum discharge would occur, i.e., E_{To}.

OUTFLOW

Unit area annual discharges (cm) based on areas of 1.64 ha and 0.109 ha are shown in Fig. 5, along with E_T values calculated as Oct/Sep precipitation minus discharge. Regression of control plot discharge E_T values against Oct/Sep precipitation reveals a highly significant relationship, with an r^2 of 0.59 and a S.E. (slope) of 0.075.

$$E_T = 33.1 + 0.284x \tag{4}$$

where x is Oct/Sept precipitation

This indicates that about 28% of each increment of precipitation above E_{To} would serve to increase E_T, while the remaining 72% would contribute to increased discharge. From Eqn. (4), E_{To} can be calculated to be 462 mm. In this case, E_{To} is not the intercept but is the point at which y = x, i.e., precipitation is equal to E_T. While this estimate is the same as that shown above, it cannot be considered to be independent, as it is calculated from the same data. A similar estimate of the fraction of the precipitation that contributes directly to increased outflow may be obtained from the ratio 1.173/1.639, i.e., the ratio of the area as estimated using the snow plus Apr/May precipitation to the area estimated using the full year cycles. This ratio also suggests that about 72% of each increment of precipitation above E_{To} contributes to outflow, while the remaining

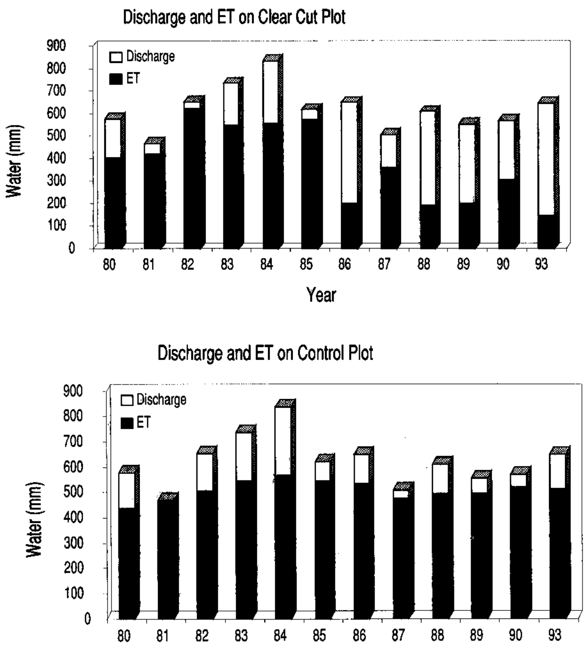

Fig. 5. *Discharge and E_T by years. Clearcut plot harvested in late 1984. Based on areas of 0.109 ha and 1.639 ha for clearcut and control plots, respectively.*

28% contributes to increased E_T. Thus, for $P > E_{To}$, outflow (mm) would be predicted by,

$$Q = (P - 46.2)\ 0.716 \tag{5}$$

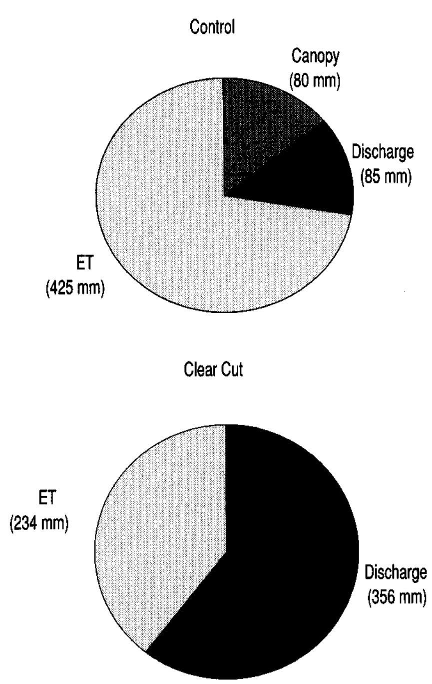

Fig. 6. *Summary diagram showing the mean fate of precipitation on the control and harvested plots during the six post-harvest years that were monitored (1986–90 plus 1993). Mean total precipitation was 590 mm.*

and at the mean precipitation of 596 mm, the estimated E_T would be 500 mm.

The 12-year mean discharge from the control plot is 112 mm. During the pre-cut period, 1980–84, precipitation was relatively high and discharge averaged 144 mm for the plot scheduled for cutting and 152 mm for the control plot. Starting in 1986, discharge from the control plot averaged only 85 mm while discharge from the clearcut plot averaged 356 mm, apparently a more than four-fold increase due to clear cutting. (Fig. 5). The discharge and E_T for the post-harvest control and clearcut plots are summarized in Fig. 6. The canopy loss from the control plot may also be considered to be a component of E_T, but it is depicted separately on the graph to provide a perspective on the importance of this process. The more than four-fold relative increase in discharge due to timber harvest may be somewhat exaggerated due to the relatively dry period when discharge from the control plots was relatively low, but the absolute increase in discharge was a very substantial 271 mm.

Discussion

For a mixed conifer stand at FEF, this plot experiment provides independent estimates of several hydrological parameters and the results are entirely consistent with previous estimates derived from various studies. For example, the increase of 34% in PWE of the snowpack as a result of clear cutting is very close to the 36% predicted to occur under similar conditions by Troendle (1987). The estimated E_T of 462 mm at zero discharge and 500 mm for a mean rainfall of 596 mm is consistent with the range of 450 mm to 570 mm given by Troendle and King (1985), Troendle (1987), and Troendle and Kaufmann (1987). Previously, Troendle and King (1985) had observed a mean E_T reduction of 82 mm (estimated as the change in flow) for the 30 year period following timber harvest on Fool Creek. Secondary analysis indicated that, under an average precipitation, and in the absence of a recovery effect, the increase in flow, or reduction in E_T, would average 100 mm at the catchment level. Assuming a linear effect of area harvested, this would correspond to a mean of 250 mm from the area actually harvested. The 6-year mean estimate of increased outflow of 271 mm for a 100% clearcut on plot 1 agrees quite well with the catchment observation. The authors are unaware of any previous reports of the indirect method of calculating the area of unbounded plots based on the relationship between discharge and precipitation input. The correspondence of the hydrological parameters to those previously determined by other methods lends considerable credence to the validity of both the hydrological parameters and the estimates of plot area. The estimate given here of the dependence of E_T on precipitation, i.e., 28% (S.E. 7.5%) of precipitation above an E_{To} value of 462 mm contributing to increased E_T rather than to discharge, was not previously available for this site. In addition to providing independent estimates of hydrological parameters, the water flux values given here can be combined with available chemical data to provide estimates of biogeochemical fluxes, which are reported separately (Reuss *et al.*, 1997).

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